Sustainability assessment of steel fibre reinforced concrete pavements

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Abstract

The current scenario of depleting resources has lead to a major thrust in developing and applying highly sustainable solutions to construction industry. Therefore, it has become essential to devise designs based on materials that cost the least for the transportation network and at the same time have a minimum environmental impact. Though there are a few modern material solutions that may meet these criteria, like the use of steel fibre reinforced concrete (SFRC) for pavement constructions, a proper evaluation of the performance and impact of utilization of such materials is lacking. Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) offer the means to evaluate the sustainability, and have been used in this paper to provide frameworks analysing Asphalt, Jointed Plain concrete (JPC) and Steel Fibre Reinforced Concrete pavements. In this work, asphalt, JPC and SFRC pavement sections have been designed as per the respective IRC guidelines so as to get equivalent designs for the given traffic loading, environmental and material conditions. Subsequently, LCCA is done as per the procedure provided in the Federal Highway Administration's Interim Technical bulletin and LCA is done by using the process approach for each of the pavements. The assessment indicates where sustainable practices can be directed to so as to minimize environmental impacts in the initial stage of the pavement life cycle. The paper also discusses the limitations and difficulties of carrying out life cycle assessment and life cycle cost analysis for highways in India.

Keywords: Life cycle analysis, sustainability, rigid pavements, steel fire reinforced concrete, flexible pavements

1. Introduction

In almost every part of the world, pavements have shown premature distress, which results in frequent replacement of the existing surface. Often, though the construction cost of the pavements is low, the maintenance costs are very high and time is lost due to frequent resurfacing and replacement. Due to the current scenario of depleting resources, it has become essential to devise designs based on materials that cost the least for the entire transportation system life and at the same time have minimum environmental impact over a sufficiently large analysis period. Though there are a few modern material solutions that may meet these criteria, like the use of steel fibre reinforced concrete (SFRC) for pavement constructions, a proper evaluation of the performance and impact of utilization of such materials is lacking. In addition, maintenance budgets are more often than not insufficient, thereby requiring the optimal usage of funds for repair and rehabilitation (Kadiyali and Dandavate 1984). This necessitates a proper evaluation technique for the performance and economics of the pavements throughout the life cycle so as to obtain sustainable solutions (Kadiyali and Dandavate 1984, Chakravarty and Kadiyali 1989, Dandawate 1993).

Sustainability in the construction scenario would essentially require a design that takes care of durability throughout its functional service life, a construction methodology which would cause the least harm to the environment and also reduce the effect of disposal by reusing and recycling the materials at the end of life phase, and all these in the most economic way (Swamy 2001). Integrating sustainability requirements in the design so as to find an intersection between environmental impact initiatives and financial benefits is definitely a challenge faced by most of the infrastructure developers today.

In general, any sustainability study would point towards three facets, viz., Environmental impact, Economic impact and Social impact. A proper assessment technique of each of these three spheres of influence is essential to obtain the maximum benefit with the minimum negative impact (Muga 2009). An integrated life cycle assessment and life cycle cost analysis framework would be the most appropriate solution when coupled with some sort of social impact assessment. The life cycle assessment would result in obtaining a clear picture about the environmental loads related to the project (Josa et al. 1999, Josa et al. 2005) while the life cycle cost assessment would enable amalgamating economics into the process so as to direct funds and resources in the most productive manner. The most difficult factor to assess and quantify is the social cost (e.g., comfort, aesthetics, noise, effect of providing access and traffic movement) of the project. As a result, though vaguely included in the existing assessment techniques, it cannot be fully ascertained nor can it be completely ignored.

2. Life Cycle Assessment (LCA)

Lifecycle assessment is a process to understand and estimate the environmental impacts of a product throughout its lifecycle (Häkkinea and Mäkelä 1996, Josa et al. 1999, Zapata and Gambatese 2005, Muga 2009). It is typically also referred to as “cradle to grave” analysis since LCA should ideally include all phases of a product life cycle from the raw material extraction phase to the end of life/recycling phase (Horvath and Hendrickson 1998, Maija et al. 1999, Stripple 2001, Josa et al. 2003, Santero et al. 2010). LCA generally involves four stages of analysis as shown in figure 1 below (Josa et al. 1999, Stripple 2001, Josa et al. 2003, Josa et al. 2005, Santero et al. 2010)

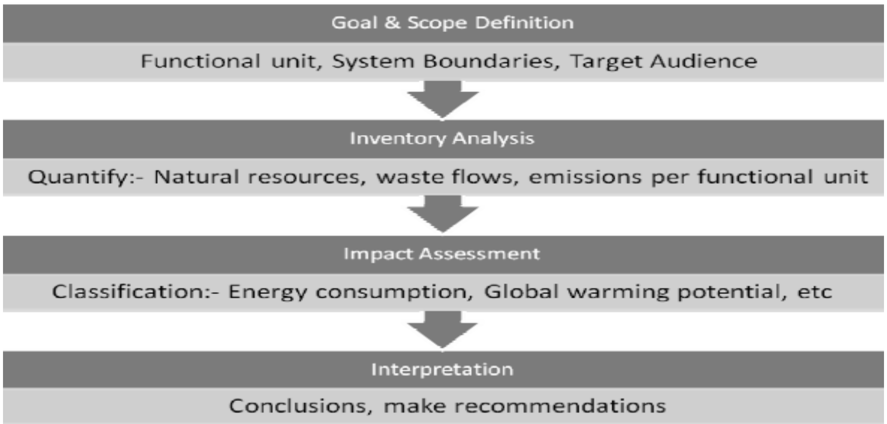


Figure 1.Stages in life cycle assessment and associated factors

2.1 Basic LCA Framework modified for pavements

The general LCA framework has been modified by many researchers and tailored specifically for pavements (Horvath and Hendrickson 1998, Ulla-Maija et al. 2000, Huang 2008, Miller and Bahia. 2009, Santero et al. 2010). The general features of such a framework are discussed below. For LCA specific to pavement application, the functional unit is defined in terms of analysis length, analysis period and the volume of traffic that would use the facility during the analysis period. System boundaries correspond to the pavement phases that are considered in the analysis and the processes considered in each phase.

2.1.1 Inventory Analysis

It is mostly useful to compartmentalise the data required for inventory analysis of pavements. From the review of existing literature, a suitable method of data compartmentalisation can be as summarised in the figure 2 below (Stripple 2001, Miller and Bahia 2009, Santero et al. 2010).

In order to identify the specific phases and processes that cause maximum environmental impact, it is suitable to segregate the pavement life into different phases (Santero et al. 2010). This modular approach will help identify and direct sustainable practices to these phases, and thus minimize the impact of the process as a whole. A logical classification of these phases has been proposed by Santero (2010) that is widely accepted and is summarized in figure 3 below.

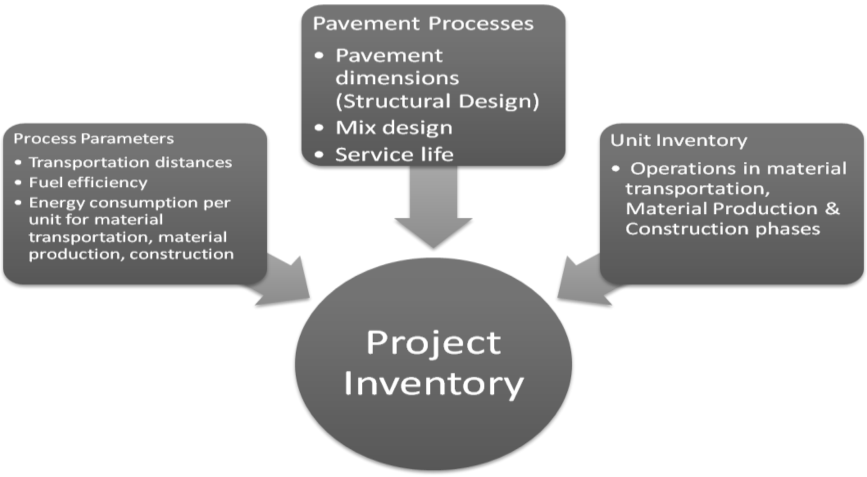


Figure 2 Compartments of the inventory data

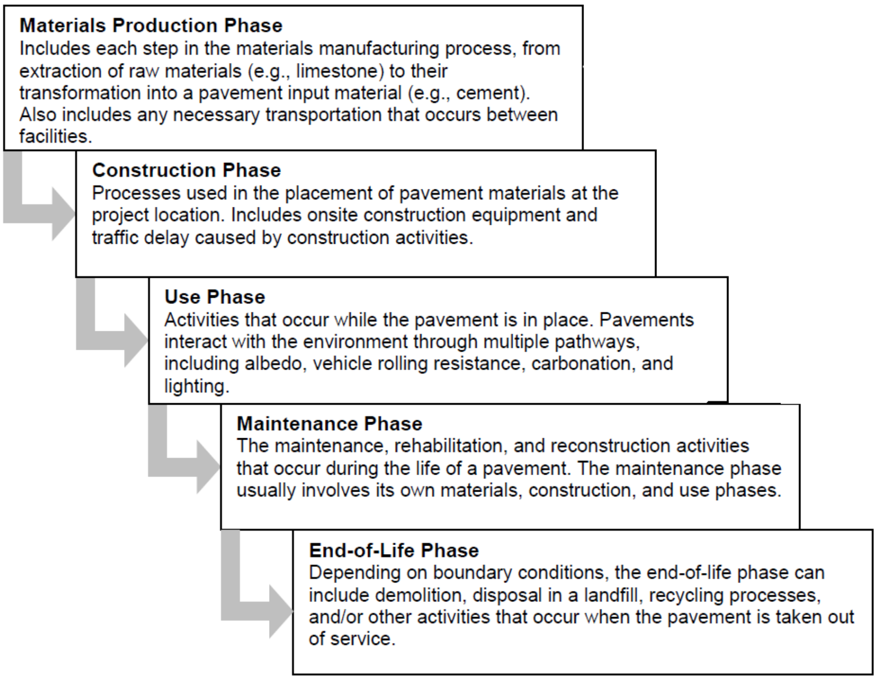


Figure 3.Phases in pavement lifecycle that may be assessed in LCA

2.1.2 Impact Assessment

From the inventory, the results are classified, characterized and assessed to finally arrive at a single value indicator that would follow from a general list of impact categories. However, the list of impact categories is not very comprehensive so as to make the task of choosing the right effect for a particular application easy. Due to this limitation, most of the existing life cycle assessment studies for pavements are restricted to being a life-cycle inventory (LCI) rather than true life cycle assessment. However, some of the results are close enough to the impact categories themselves (Santero et al. 2010).

From the review of the existing literature, it is understood that, most commonly, the output of these studies amounts to energy consumption data that cannot be easily translated to impact parameters. Another common but more appropriate indicator is the CO_2 emission, which can be directly taken as an indicator of global warming potential. Some of the uncommon indicators used are air pollutants, hazardous waste generations, green house gases, nitrogen release, heavy metal release, noise, water consumption, etc. These categories could as well be inventoried pollutants rather than impacts and better related indicators could be human toxicity, eutrophication, acidification, etc (Häkkinea and Mäkelä 1996, Horvath and Hendrickson 1998, Maijaet al. 1999, Stripple 2001, Santero et al. 2010).

2.1.3 Interpretation

Analysis of the results to direct improvement plans towards the most beneficial route is the aim of this step. The choice of different pavement alternatives or modifying specific processes in a chosen alternative is to be essentially done using the single value indicators developed during impact assessment (Josa et al. 1999). The assessment results would indicate the area where sustainable practices can be directed to so as to minimize environmental impacts in the initial stage of the pavement life cycle.

3. Life cycle cost analysis (LCCA)

In addition to the environmental impact, it is extremely important to analyze the economic impact of the project throughout the lifecycle in order to arrive at the most suitable solution. This is especially so in large scale projects like pavement construction, where maintenance cost is as significant as the initial cost. Lifecycle Cost Analysis (LCCA) is a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoring and resurfacing costs (TEA 21, 1998). The essence of life cycle costing for pavements is basically to capture all predictable costs that may have an impact on the economy/society that could be affected by the highway pavement project under consideration (Wilde et al, 1999).

3.1 LCCA framework for pavement application

Figure 4 describes the procedure adopted by the State Department of Transportation in USA for comparing lifecycle costs across different pavement design alternatives (Walls and Smith, 1998, NCHRP document, 2004). It is to be noted that the framework provided in the figure 4 below can be applied to compute life cycle costs for any type of pavements, and is not specific to any particular pavement type (i.e., flexible or rigid).

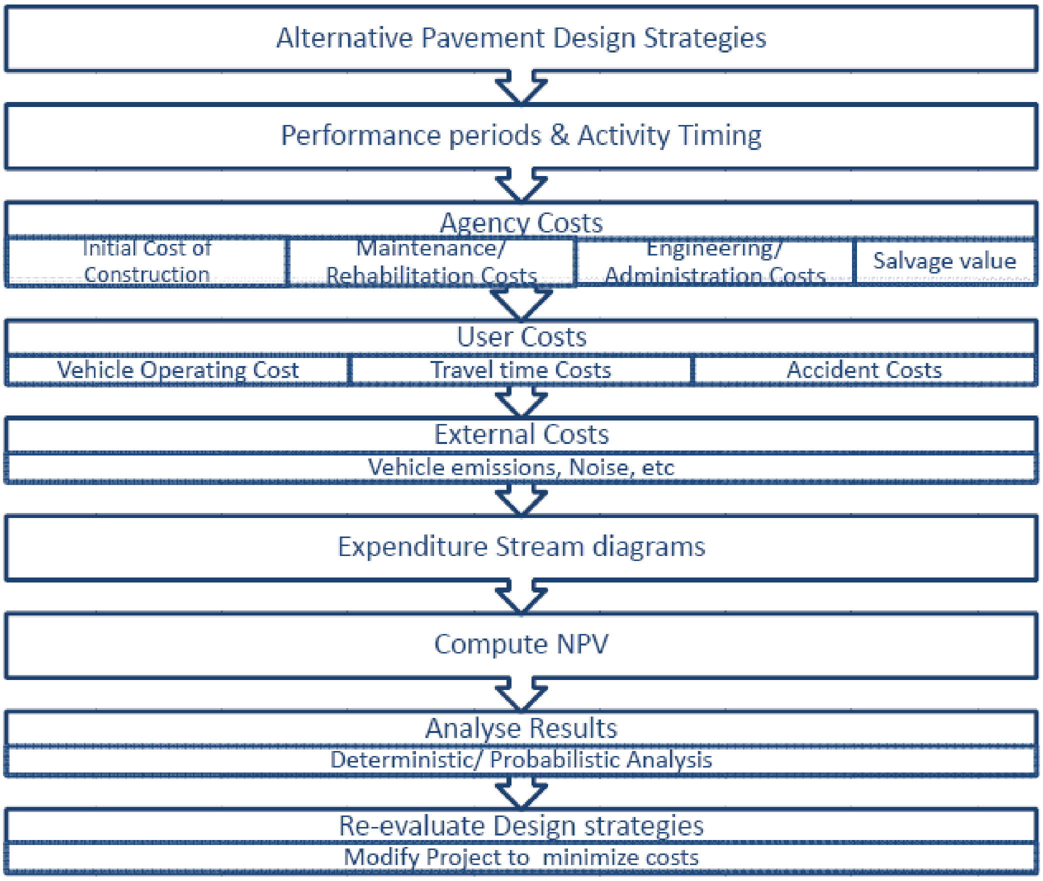


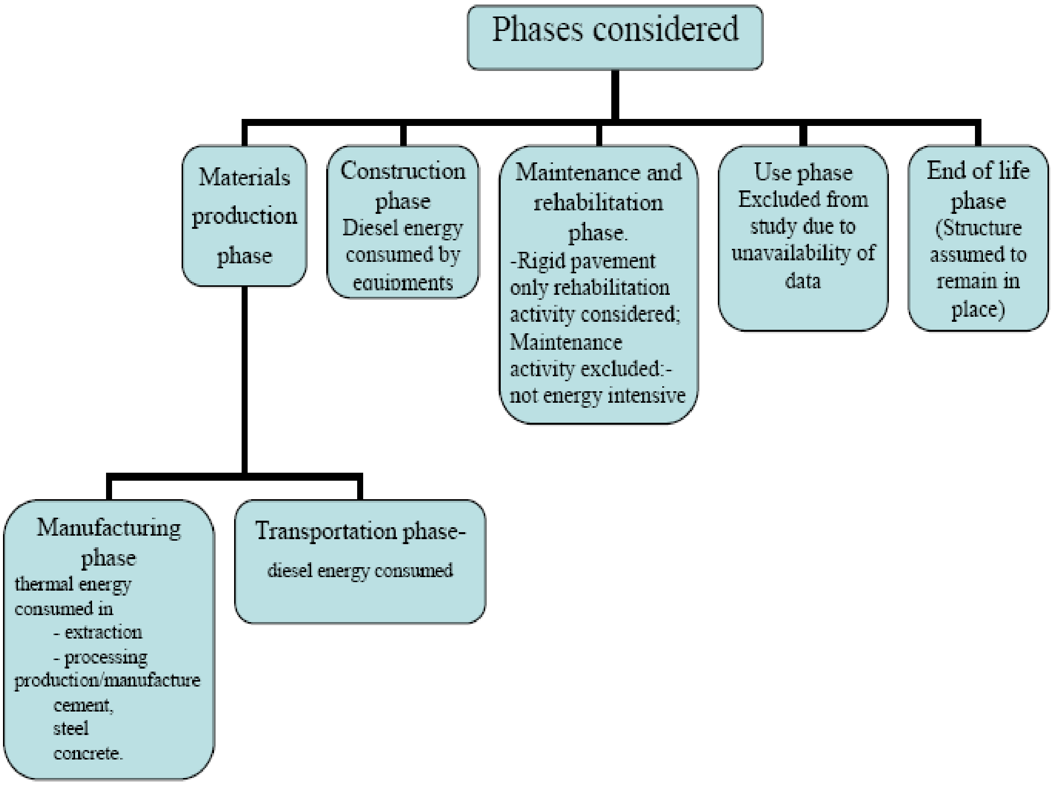
Figure 4.Steps in LCCA for pavements

4. Case study - LCA details of the study

For the purpose of comparing the feasibility of pavement alternatives in India, LCA and LCCA of three types of pavements, namely Asphalt pavements, Jointed plain concrete pavements (JPCP) and Steel fibre reinforced concrete pavements (SFRCP) were done with the data available. Here, the process-based approach was adopted for LCA. A national highway upgradation project in the vicinity of Chennai (India), nearing completion, was selected for the study. The unit rates and technical specifications for labour, material and equipment used in the analysis are typical of those encountered in highway construction for Chennai.

National highways are generally designed considering a soaked CBR value of 10% which corresponds to a modulus of sub-grade reaction of 5.5 $kg/cm^2/cm$ (IRC 58:2002). For the calculation of temperature stresses developed in the slabs of concrete pavement, the highway has been assumed to lie in a coastal area unbounded by hilly zones (i.e., Zone VI). The dowel and tie bar quantity for the concrete pavements is based on the 98 percentile axle load taken to be 16 tonnes (IRC 58:2002). The total traffic (in both directions) at the end of the construction period on the four lane highway was obtained from assumed traffic data as 11,163 vehicles per day (IRC 58: 2002, D'costa 2011).

The functional unit for this study is a one km long stretch of the widened lane in each direction of the highway. The scope of the LCA includes the materials and energy consumed in construction and maintenance of asphalt, JPCP and SFRC pavements over a 40 year period. The phases considered are given in the flowchart below. Note that gaseous emissions have been excluded from the study.



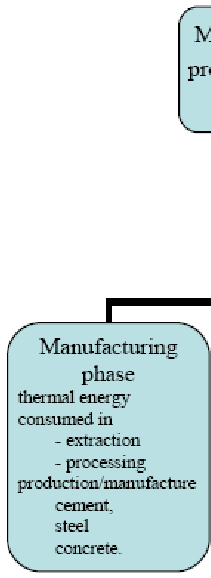
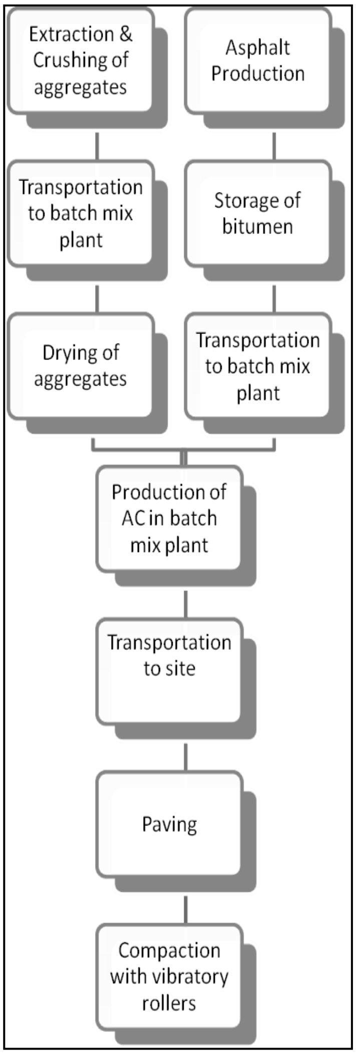


Figure 5. Different phases considered in the current study

In the analysis, the following assumptions had to be made. Transit mixers and tipper trucks are assumed to have the same speed while loading and unloading. The distance from the Hot Mix Asphalt batch mix plant and Ready Mix Concrete plant to the construction site was assumed to be same. The rehabilitation schedule for SFRC pavements was assumed to be same as that for JPCP due to lack of data since most of the SFRC pavements are very recent and have not warranted any rehabilitation. Temperature stresses developed in a SFRC slab was assumed to be the same as that developed in a plain concrete slab. Also, for this analysis, the energy consumed for the production and transportation of water, superplasticisers and high density polythene sheet has been excluded. The energy consumed for transformation processes like drawing of steel fibres from steel wires, etc. has been neglected since the overall contribution of this process to the total energy consumed is considered very minimal.

The hierarchy for the processes considered (i.e., the material supply chain) in the construction of the pavement layers is shown in the figures 6 & 7 below. The processes for JPCP are same as that for SFRC excluding the fibre manufacturing and/or the fly ash manufacturing and thereby are not shown separately.



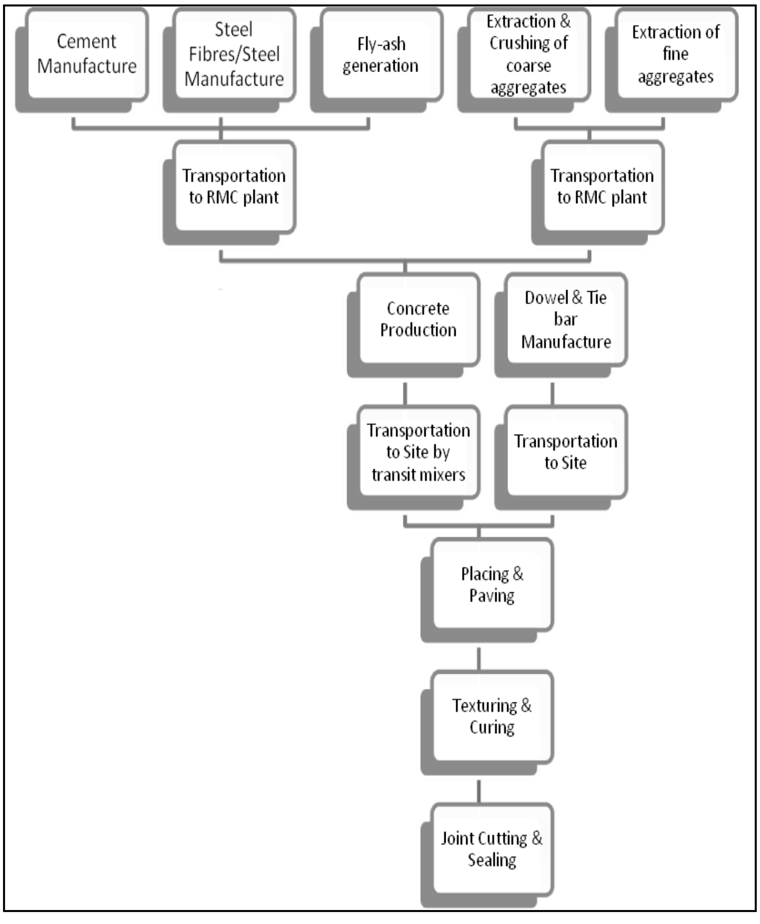


Figure 6 Asphalt pavement processes

Figure 7 SFRC/ JPCP pavement process

Flexible pavements were designed as per IRC 37:2001 based on traffic in the lane carrying the maximum number of commercial vehicles. The method of design is not discussed here as it is well established (IRC 37:2001) and the details are given in Table 1Table 1. The mixture proportions for the bituminous layers and the aggregate gradation for the non-bituminous layers were assumed to be the same as that given in the NHAI data book since they are in accordance with the respective IRC and Ministry of Road Transport and Highway (MORTH) specifications.

Only the Pavement Quality Concrete (PQC) layer was varied across the concrete pavement alternatives while the drainage layer and the Dry Lean Concrete (DLC) layer were kept constant. Most of the rigid pavements (using normal concrete without any cement substitution) in India are designed to have a 28-day characteristic cube compressive strength of at least 40 MPa, which corresponds to a flexural strength of about 4.43 MPa. As per IRC 58:2002, this value can be rounded off to 4.5 MPa for design purposes. The design of JPCP was entirely done based on IRC 58:2002 and the design thickness of pavement was obtained as 320 mm with M40 grade concrete.

Table 1 Flexible pavement design details

Layer	*Thickness (mm)*	*Width (m)*
Granular sub-base (GSB)	*200*	*8*
Wet mix macadam (WMM)	*250*	*8*
Dense Bituminous Macadam (DBM)	*81*	*7*
Bituminous concrete (BC)	*40*	*7*

In this work, the design of SFRC is done as per the specifications of IRC SP: 46, 1994 and IRC 58:2002. As the flexural strength was the design criteria and was assumed to be same (4.5 MPa) for both SFRC and JPCP, the design thickness for SFRC is the same as that of JPCP since the design methodology as per IRC 58 :2002 considers only the design flexural strength. However, the enhanced flexural capacity of SFRC was used to change the concrete grade requirement by incorporating the expression $(1+R_{e,3})\times f_{ct}$ in the required flexural strength calculation, where $R_{e,3}$ is the equivalent flexural strength ratio of SFRC (Note that the equivalent flexural strength is a toughness parameter obtained from flexural testing of SFRC beam specimens as per standards such as ASTM 1609-2010 or JSCE SF4- 1984). This resulted in a lower requirement for f_{ct} in comparison to plain concrete as $R_{e,3} > 1$ always. M25 concrete with 10 and 15 kg/m^3 hooked-ended cold-drawn steel fibre dosage could normally give characteristic design flexural strengths of 4.34 MPa and 4.83 MPa, respectively. Accordingly, an M25 grade concrete with a dosage of 12.5 kg/m^3, which corresponds to a characteristic flexural strength of approximately 4.5 MPa was selected for the design.

Since the 28 day characteristic compressive strength required for SFRC was 25 MPa while that for the plain concrete pavement was 40 MPa, the quantity of dowel bars required per lane was 4.56 tonnes and 6.66 tonnes, respectively (IRC 58: 2002).

Based on the above data, the materials consumed by each of the pavement types considered per functional unit are obtained and summarized in the Table 2 below

Table 2 Material consumption

Pavement Alternative	*Aggregates (cu.m.)*	*Bitumen (tonne)*	*Steel (tonne)*	*Diesel (L)*
Flexible pavement	*9620*	*492*	*0.0*	*7770*
JPCP	*4315*	*1027*	*14.9*	*5205*
SFRCP	*4225*	*874*	*49.3*	*5176*

The energy consumed by each of the alternatives per functional unit in each phase of the pavement life cycle is shown in the Table 3 below.

Table 3 Energy Consumption (GJ) across pavements

Pavement Alternative	*Manufacturing*	*Transport*	*Placement*	*Maintenance*	*Total*
Flexible	*1180*	*534*	*77*	*5300*	*7090*
JPCP	*6640*	*848*	*90*	*742*	*8320*
SFRC	*6160*	*791*	*890*	*557*	*7600*

From the results it can be seen that when assessing the impact due to material consumption, asphalt pavements definitely result in higher impact when compared to the rigid pavement alternatives. The aggregates consumed by asphalt pavements are more than double that required by an equivalent JPCP or SFRC pavement, as can be seen in table 2, which is a factor that would outweigh many other advantages that asphalt pavements seem to have. The major disadvantage of rigid pavements seems to be in the high energy consumption. However, the most energy intensive process in construction of concrete pavement is the construction of the PQC layer as can be seen from table 3; this is on account of the large thickness (320 mm) of the PQC layer in comparison to the asphalt alternative in which the bituminous layer is only 121 mm thick.

Though SFRC has higher flexural crack resistance compared to normal concrete, the high amount of energy consumed in the manufacture of steel fibres overpowers the advantage of having a lower grade of concrete. It is noted at this juncture that for the current study, the design thickness was kept constant for both JPCP and SFRC because both the pavements were designed for the same flexural strength using the same design principles. However, an appropriate inelastic design procedure for SFRC pavements would lead to a much lower thickness design, as suggested by many researchers and codes (Losberg 1961, Meyerhof 1962, IRS SP: 46, 1994, TR- 34 2003). Such design would definitely result in a lower energy consumption requirement resulting in the SFRC pavements having minimum energy impact as compared to asphalt and JPCP pavements.

5. LCCA for the case study

Deterministic life cycle cost analysis was done for the given LCCA parameters for a period of 40 years since the concrete pavements are expected to undergo rehabilitation after 35 years (Bongirwar and Momin, 2000). A discount rate of 12% was used as per the Government of India norms. A traffic growth rate of 4% was used since the four lane highway reaches its capacity at 44 years for the given growth rate.

The relative proportion of the different vehicles is assumed to remain constant throughout the analysis period. The work zone user costs associated with the initial construction phase has been excluded as the analysis period is assumed to begin from the commercial operation date. Also, it is assumed that there is no change in the traffic volume in the given facility when a work-zone is in place.

The periodic maintenance schedule for rigid pavements consists mainly of two activities that are Joint seal renewal and diamond grinding (Bongirwar and Momin 2000, Prasad 2007). The periodic maintenance for a standard flexible pavement in India includes surface renewals with 25 mm bituminous concrete (BC) (Prasad 2007).

The timing assumed for maintenance and rehabilitation activities of flexible pavements was taken as given in table 4 below while that for rehabilitation activities of rigid pavements was in accordance with specified in the Caltrans LCCA Manual 2007 and is given in table 4.

Table 4.Maintenance and rehabilitation activity timing and cost

M&R Activity	*Frequency (Years)*	*Service Life (Years)*	*Lane closure time per lane km (hours)*	*Cost per lane km (in millions of Rs.)*
Surface renewal	*5*	*5*	*3*	*0.62*
Overlays	*10*	*5*	*5(BC)+9(DBM)*	*2.61*
CPR-Type C	*At 35 years*	*5*	*13*	*2.19*

The initial cost of construction for a two lane national highway across the different types of pavement alternatives is given in table 5 below.

Table 5 Initial Cost of construction (using present market unit rates for labour, material and equipment)

Pavement Type	*Cost (in millions of Rs. per lane km)*
Asphalt	*10.77*
JPCP	*14.40*
SFRC	*17.55*

The traffic data was classified into three main categories of passenger car units, single unit trucks (SUTs) and combination unit trucks (CUTs) based on the assumption that SUTs and

Table 6 Value of User time

CUTs correspond to single axle loads and tandem axle loads respectively. The value of user time across the different vehicle categories is summarized in the table 6 below

Pavement Type	*Life Cycle Agency Costs (Rs in millions)*	*Life Cycle User Costs (Rs in millions)*	*Life Cycle Costs (Rs in millions)*
Asphalt	*14.8*	*0.052*	*14.85*
JPCP	*14.5*	*0.075*	*14.58*
SFRC	*17.6*	*0.075*	*17.68*

As can be seen from the table 6, the value of user time for SUTs are comparatively higher than the other vehicle categories primarily due to higher vehicle occupancy.

The Vehicle operating costs (VOC), excluding taxes per unit vehicle for each vehicle class, for a four lane divided highway were calculated based on the equation for VOCs as provided in URUCS 2001 (CRRI 2001). The Net present value (NPV) for rigid pavements was accordingly estimated to be Rs. 72.31 million. Since asphalt pavements receive surface renewals every five years it can be assumed that the roughness is lower than rigid pavements and accordingly the estimated NPV is only Rs. 63.1 million. Finally the net present value of the life cycle agency and user costs for the different alternatives is summarized in table 7 below.

Table 7 Life Cycle Costs

The total life cycle cost for JPCP works out to be the lowest compared to the asphalt and SFRC pavements, which is a positive indication for sustainable practices. However, the higher life cycle cost for SFRC pavement is solely due to the thickness design which is the same as JPCP and a more economical solution would be obtained if more appropriate design could be incorporated.

Vehicle Category	*Value of user time (Rs/hour)*
PCUs	*127*
SUTs	*734*
CUTs	*115*

6. Conclusions

The following conclusions can be made from the work presented here:

- LCA and LCCA seem to be good tools for assessing the sustainability of the processes in pavement construction.

- For the case study considered here, asphalt pavements consume the least energy for the given traffic, environmental and subgrade conditions. The LCCA results indicate that jointed plain concrete pavements (JPCP) would be a good choice for sustainability. However, a properly designed SFRC pavement with a reduced thickness would definitely yield better results in terms of economy.

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